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Regional Differences in the Economic Feasibility of Advanced Biorefineries: Fast Pyrolysis and Hydroprocessing

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Keywords
fast pyrolysis, techno-economic analysis, regional sensitivity, Bioeconomy Institute, Mechanical Engineering

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Introduction

U.S. renewable energy policy debates in the 21st century have been dominated by the twin issues of the country's dependence on foreign petroleum supplies and greenhouse gas (GHG) emissions from the combustion of petroleum-based fuels. An early attempt to address both concerns through the increased use of grain ethanol has provoked a significant backlash in the forms of the "food versus fuel" (Ferrett, 2007) and indirect land-use change (ILUC) debates (Searchinger et al., 2008). More recently, pathways employing lignocellulosic (i.e., non-food) biomass as a feedstock for renewable hydrocarbon production have attracted attention due to their ability to sidestep these controversies. One such pathway within the thermochemical platform is fast pyrolysis, which rapidly heats lignocellulosic biomass to decompose it into a liquid (bio-oil), a solid (char), and non-condensable gases (NCG). Bio-oil can be upgraded into monomeric hydrocarbons via reaction with hydrogen (Elliott et al., 2009) and/or catalysts (Adjaye and Bakhshi, 1995). These hydrocarbons can serve a number of important functions, including as blendstock for renewable gasoline and diesel production (so-called drop-in biofuels because of their compatibility with the existing transportation fuel infrastructure) (Holmgren et al., 2008) and commodity chemicals production (Vispute et al., 2010; Zhang et al., 2011).

The fast pyrolysis pathway will only serve as an adequate substitute for petroleum production if it proves to be economically feasible. While several studies have either directly or indirectly quantified the feasibility of different aspects of the pathway under different scenarios, most techno-economic analyses (TEA) in the literature focus on factors such as feedstock supply logistics (Hess et al., 2009; Petrolia, 2008), biorefinery size (Islam and Ani, 2000; Wright et al., 2008), production of high-value products and co-products (Ahmad et al., 2010; Brown et al., 2011a; Brown et al., 2011b; French et al., 2010; Galinato et al., 2011; Wright et al., 2010a; Yoder et al., 2011), and product yield improvement (Ahmad et al., 2010; Akhtar and Amin, 2011; Carlson et al., 2011; Yoder et al., 2011). Only a handful of TEA studies have considered politico-economic factors. McCarl et al. (McCarl et al., 2009) quantify the economic feasibility of slow pyrolysis under a scenario in which char qualifies for GHG offset credits as part of a hypothetical carbon price program. Brown et al. (Brown et al., 2011a) compare the 20-year internal rates of return (IRR) of slow pyrolysis and fast pyrolysis facilities under a scenario simulating the American Clean Energy and Security Act, in which petroleum-based transportation fuels become more expensive due to the implementation of a carbon price and biochar qualifies for GHG sequestration credits. Brown and Hu (Brown and Hu, 2011) quantify the economic feasibility of a fast pyrolysis and upgrading biorefinery under a number of different legislative and regulatory scenarios, both existing and proposed.

Factors that have not been explicitly examined in TEAs on the fast pyrolysis pathway are those that are region- and state-specific. Feedstock cost, feedstock type, product yields, capital costs, operating costs, income tax rate, and transportation fuel market values are all affected by biorefinery location. Many biomass feedstocks are region-specific, with many types confined to determinable geographic locations (Lewandrowski et al., 2004; ORNL, 2011). Feedstock type in turn determines feedstock costs at the biorefinery (Council and Production, 2011), bio-oil composition (Elliott et al., 2009), and product yields (Elliott et al., 2009; Kuzhiyil et al., 2011). Capital and labor costs vary by ±20% depending on the state (DOD, 2011) or city (Anon, 2008, 2012a; DOD, 2011) in which the biorefinery is located. The income tax rate imposed on corporations by individual states ranges from as low as zero (South Dakota) to as high as 12% (Iowa) (Anon, 2012b). Finally, pre-tax transportation fuel market values vary by ±10% depending on geographic region (API, 2012; EIA, 2012a). The economic feasibility of the fast pyrolysis and hydroprocessing pathway is sensitive to many of these factors individually (Brown et al., 2011a; Wright et al., 2010a), suggesting that it will also be sensitive to location, which affects all of these factors simultaneously.

Pathway sensitivity to location-specific factors could have important implications for the revised Renewable Fuel Standard (RFS2) in the U.S. The RFS2 mandates the utilization of 136 billion liters per year (BLY) of biofuels within the U.S. by 2022 (EPA, 2010). 61 BLY of this total volume must come from cellulosic biofuels, which are defined as those produced from lignocellulosic feedstock and achieving a lifecycle GHG reduction threshold relative to gasoline of at least 60%. The fast pyrolysis and hydroprocessing pathway qualifies as a cellulosic biofuel pathway under the RFS2 definition when lignocellulosic feedstock is utilized (Hsu, 2012). Qualifying as a cellulosic biofuel allows commercial-scale facilities employing the pathway to earn compliance commodities called Renewable Identification Numbers (RIN), which attach to each liter of cellulosic biofuel produced in or imported into the U.S. (Schnepf and Yacobucci, 2012). RINs are a flexible market-based subsidy designed to encourage the production of cellulosic biofuels by increasing in value to the point necessary to incentivize sufficient production to meet the volume mandated for a given year under the RFS2 (McPhail et al., 2011). RIN values operate as a function of both petroleum prices and feedstock costs, increasing in value both when petroleum prices (and gasoline and diesel fuel prices by extension) fall and feedstock costs rise. To prevent the subsidy from providing windfall profits to cellulosic biofuel producers, however, RIN values fall when petroleum prices rise and when feedstock costs fall, or when production exceeds the mandated volume. In other words, RIN values do not exceed the amount required by cellulosic biofuel producers to produce the mandated volume.

In the early stages of the mandate, when total production falls short of the mandated volume (as is currently the case) (Schnepf and Yacobucci, 2012), RIN values are high enough to ensure that all facilities employing qualifying cellulosic biofuel pathways receive enough of a subsidy to avoid operating losses. Qualifying facilities with the lowest fuel production costs receive the same “core” RIN value (i.e., excluding transaction costs and speculative impacts on value) as qualifying facilities with the highest fuel production costs and a greater profit per liter of cellulosic biofuel, thereby incentivizing production cost reductions. As total production increases to the mandated volume, RIN values decline to the lowest point necessary to incentivize production of only the mandated volume. At this point those qualifying facilities with the highest fuel production costs no longer receive sufficient value from RINs to prevent operating losses. RIN core values fall to zero when total production exceeds the mandated volume, as this value is no longer necessary to incentivize the necessary production (Schnepf and Yacobucci, 2012). In this way the RFS2 encourages a decline in production costs until RINs are no longer needed to incentivize sufficient production to meet the mandate. By initially giving the largest financial incentive to qualifying facilities with the lowest production costs and ultimately excluding those qualifying facilities with the highest production costs from fully covering those costs, the RFS2 creates an operating environment in which only the most financially-competitive facilities are able to remain profitable for the program’s duration. Strong sensitivity of the economic feasibility of a cellulosic biofuel pathway (such as fast pyrolysis and hydroprocessing) to location-specific factors could directly influence cellulosic biofuel commercialization toward a limited number of production regions. If so, accurate projections of future cellulosic biofuel RIN values will require identification of these regions.

The objective of this paper is to quantify the sensitivity of the fast pyrolysis and hydroprocessing pathway's economic feasibility to biorefinery location. This high-level scoping analysis employs a modified version of an existing process model of the pathway used in previous analyses (Brown and Hu, 2012; Brown et al., 2011a; Wright et al., 2010a) to calculate the 20-year internal rates of return (IRR) and net present values (NPV) for pathway facilities in 30 different states. Feedstock type, feedstock bio-oil yield, feedstock cost, capital cost, operating cost, state corporate income tax rate, and transportation fuel market values are adjusted for each state scenario according to the projected conditions in that state. The states are then ranked according to calculated pathway economic feasibility and a sensitivity analysis is employed to rank the individual factors according to impact on NPV.

Methodology

Location selection

The first step in this analysis is determining which states produce biomass feedstock in sufficient concentrations and volumes to enable the continuous operation of at least one commercial-scale fast pyrolysis and hydroprocessing biorefinery with a transportation fuel production capacity of 114 million liters per year (MLY) or greater (defined here as "commercial-scale"). It is not enough for total feedstock production in a state to be sufficient for this level of output, as the feedstock must also be located near enough the biorefinery to enable its economical transportation from the harvest site to the biorefinery. Results from the Geospatial Bioenergy Model (GBSM) are used to identify both the states that are capable of hosting a 114 MLY or larger advanced biofuels biorefinery and the feedstock type employed by the biorefinery (Parker et al., 2011; Parker et al., 2010). Biorefinery size is determined under the model's 2017 RFS2 $0.66/liter gasoline-equivalent (lge) scenario (Parker et al., 2010) while feedstock type is determined under the model's 2018 RFS2 scenario (Parker et al., 2011). States meeting these criteria are listed in Table 1.

Table 1. State-specific factors employed by analysis

State	Feedstock	Bio-oil yield (wt%)	Feedstock cost ($/dry metric ton)	Location capital cost factor	State corp. income tax rate	Fuel price ($/liter)
AL	Pine	70.1%	86	0.97	6.5%	0.75
AR	Switchgrass	61.4%	110	1	6.5%	0.75
CA	Douglas fir	57.8%	86	1.36	8.8%	0.83
FL	Pine	70.1%	86	0.96	5.5%	0.74
GA	Pine	70.1%	86	0.96	6.0%	0.74
IA	Stover	64.6%	101	1.11	12.0%	0.75
IL	Stover	64.6%	101	1.35	9.5%[a]	0.75
IN	Stover	64.6%	101	1.06	8.0%	0.75
KS	Stover	64.6%	101	1.06	7.0%	0.75
KY	Switchgrass	61.4%	110	1	6.0%	0.75
LA	Pine	70.1%	86	1	8.0%	0.75
ME	Pine	70.1%	86	1.17	8.9%	0.80
MI	Stover	64.6%	101	1.29	6.0%	0.76
MN	Stover	64.6%	101	1.2	9.8%	0.76
MO	Stover	64.6%	101	1.1	6.3%	0.76
MS	Oak	64.5%	86	0.98	5.0%	0.75
NC	Oak	64.5%	86	0.97	6.9%	0.74
NE	Stover	64.6%	101	1.08	7.8%	0.76
OH	Stover	64.6%	101	1.01	0.3%[b]	0.76
OK	Switchgrass	61.4%	108	1.04	6.0%	0.76
OR	Douglas fir	57.8%	86	1.16	7.0%	0.83
PA	Oak	64.5%	86	1.17	10.0%	0.79
SC	Switchgrass	61.4%	110	0.99	5.0%	0.74

SD	Stover	64.6%	101	1.12	0.0%	0.76
TN	Switchgrass	61.4%	110	0.97	6.5%	0.76
TX	Switchgrass	61.4%	108	0.89	4.5%[c]	0.75
VA	Switchgrass	61.4%	110	1.02	6.0%	0.74
WA	Douglas fir	57.8%	86	1.21	0.0%	0.83
WI	Oak	64.5%	86	1.21	7.9%	0.76
WV	Oak	64.5%	86	1.06	7.0%	0.74

[a] Includes “replacement tax” worth 2.5% of net income.
[b] 0.3% of gross receipts over $1 million.
[c] 4.5% of gross receipts after deduction for cost of goods sold.

While municipal solid waste (MSW) is included in feedstock types considered by the GBSM analysis, it is excluded from this analysis. MSW has not been the focus of much experimental research as a fast pyrolysis and hydroprocessing feedstock and there is relatively little data on bio-oil yields from MSW, let alone its hydroprocessing. Additionally, MSW differs from other feedstocks such as corn stover and switchgrass in that its composition is very sensitive to its place of origin. Whereas corn stover composition is relatively similar regardless of its place of origin, MSW composition can be expected to vary according to neighborhood source, let alone city or state. MSW also frequently contains inorganic materials such as plastics, raising the question of whether transportation fuels derived from it would be considered biofuels by the Environmental Protection Agency (EPA) and allowed to qualify for the RFS2.

Feedstock type

The majority of the non-MSW advanced biofuel facilities predicted by the GBSM employ either agricultural residues or forest resources as feedstock (Parker et al., 2011). While the model does not detail biomass type within these broad feedstock categories, it is possible to identify the most likely feedstocks by cross-referencing the predicted biorefinery locations with biomass availability data. A report by the National Research Council (NRC) (CEEIIBP and NRC, 2011) identifies the volumes and types of non-MSW lignocellulosic feedstock available to a number of the biorefinery locations identified by the GBSM, with forest, crop residues, and dedicated bioenergy crops being the most prevalent. While multiple feedstock types are sometimes listed for the projected biorefineries, only the most prevalent in each state is used in this analysis due to a lack of experimental data on the fast pyrolysis and hydroprocessing of feedstocks comprised of mixed biomass types. Feedstock types are further narrowed down by determining the prevalent biomass type in each state. For example, where the GBSM projects a biorefinery to employ agricultural residue in a state with a large volume of corn production, this analysis assumes that corn stover is the feedstock used. Forest type data from the USDA Economic Research Service (Lewandrowski et al., 2004) and Forest Service (USDA, 2000) is used to identify the prevalent type of forest in a region with a biorefinery projected by the GBSM to employ forest resources. These are categorized as Douglas fir, oak, or pine (see Table 1) due to the availability of experimental fast pyrolysis data for these feedstock types. Finally, this analysis assumes that switchgrass is employed as feedstock by projected facilities in states where dedicated bioenergy crops are projected to be most prevalent (CEEIIBP and NRC, 2011).

Feedstock cost

The NRC report (CEEIIBP and NRC, 2011) employs the Biofuel Breakeven model (BioBreak) to calculate the minimum value that a lignocellulosic feedstock producer is willing to accept (WTA) for a dry ton of feedstock delivered to an advanced biofuel biorefinery under a scenario in which the price of petroleum is $111/bbl. The WTA is calculated for a number of different feedstock types, including stover, switchgrass, and forest residue in different regions. This analysis employs the BioBreak model's calculated WTA values as the costs for the different feedstocks analyzed (see Table 1).

Bio-oil yield

An analysis of multiple experimental results on the fast pyrolysis of biomass suggests that feedstock type significantly affects bio-oil yield. This analysis calculates bio-oil yields for Douglas fir, oak, pine, and switchgrass by averaging the bio-oil yields from several different fast pyrolysis experiments for each feedstock under similar operating temperatures (474-625°C). The results are presented in Table 2.

Table 2. Product yields by feedstock

	Bio-oil yield (wt%)			NCG yield (wt%)			Char yield (wt%)		
Feedstock	Average	Median	St dev	Average	Median	St dev	Average	Median	St dev
Douglas fir (Di Blasi et al., 2001; Liaw et al., 2012; Ren et al., 2012)	57.8	57.8	1.3	17.5	16.5	10.1	23.7	27.0	9.5
Oak[a] (Czernik et al., 1994)	64.5	66.6	7.3	11.7	11.4	2.1	22.3	20.3	7.4
Pine (DeSisto et al., 2010; Kang et al., 2006; Oasmaa and Kuoppala, 2003; Oasmaa et al., 2010)	70.1	69.8	5.0	17.0	16.3	5.8	12.0	12.0	1.9
Stover (Agblevor et al., 1995; Mullen et al., 2010; Mullen et al., 2009; Zheng, 2008)	64.6	63.8	4.2	17.2	15.9	4.2	18.3	17.9	1.5
Switchgrass (Agblevor and Besler, 1996; Agblevor et al., 1995; Boateng et al., 2007; Fahmi et al., 2008)	61.4	60.7	1.6	12.0	11.4	4.0	19.2	19.5	4.9

[a] Includes unpublished data from 30 trial runs of oak sawdust fast pyrolysis in an auger reactor performed at ISU (R.C. Brown, pers. comm., 2012).

Location capital cost factor

Capital costs are sensitive to biorefinery location. A number of different location capital cost factor indices have been created for the purpose of calculating biorefinery capital costs for a given location and baseline. Examples include the Department of Defense's (DOD) area cost factors (DOD, 2011), the Richardson International Construction Factors Manual™ (Anon, 2008), and the ENR 20-city Construction Cost Index (Anon, 2012a). While the three indices produce similar location factors for a given location, they are not all equally suited for this analysis. The ENR 20-city Construction Cost Index is limited in both size and area; in addition to covering only 20 U.S. locations, it focuses on urban areas that are unlikely to host non-MSW fast pyrolysis facilities due to property expense, zoning restrictions, and a lack of non-MSW feedstock in close proximity. The Richardson International Construction Factors Manual™ covers 38 U.S. locations but, in addition to also focusing on urban areas, does not cover many of the states included in this analysis. The DOD's area cost factors are available for hundreds of locations, both urban and rural, covering all U.S. states. Furthermore, an analysis of the Richardson factors and DOD's area cost factors for 2007 shows that they are very similar to one another for most U.S. locations, generally agreeing within 5% (Anon, 2007, 2008) despite the DOD's factors nominally being intended for military rather than commercial construction.

This analysis employs the DOD's area cost factors to calculate capital costs for a given location. This index is based on local costs for a basket of eight labor jobs, 17 construction materials, and four equipment items, as well as accounting for factors such as local weather, seismic, and climatic conditions (DOD, 2011). The state average area cost factors are employed for each state included in this analysis. The process model used to calculate the baseline capital cost employed by this analysis is on a U.S. Gulf Coast basis. The DOD's area cost factors are adjusted to place them on the same baseline basis by using the average area cost factor for Louisiana as unity. The resulting location capital cost factors employed by this analysis are provided in Table 1.

State corporation income tax rate

In addition to a federal corporate tax rate of 35%, this analysis also incorporates the applicable state corporate tax rate for each scenario. These are highly variable, ranging from zero in South Dakota to 12% in Iowa (Anon, 2012b). While most states employ a simple income tax rate, Illinois, Ohio, and Texas are modeled slightly differently. Illinois levies a 7% corporate income tax rate as well as a "replacement tax" rate of 2.5% that is essentially an income tax by another name. The Illinois corporate tax rate of 9.5% used in this analysis is therefore the sum of the two. Ohio has replaced its corporate income tax with a Commercial Activity Tax equal to 0.26% of gross receipts over $1 million. Texas levies a similar Franchise Tax equal to 1% of total revenues. The Ohio and Texas taxes are modeled here as taxes on gross receipts rather than net income. A full list of the state corporate income tax rates employed by this analysis is presented in Table 1.

Transportation fuel market value

The market prices of gasoline and diesel fuel vary significantly across U.S. geographic regions. The Energy Information Administration (EIA, 2012a) publishes historical weekly price data for both fuels dating to May 1997 for the New England, Central Atlantic, Lower Atlantic, Midwest, Gulf Coast, Rocky Mountain, and West Coast PADD regions. None of the states in the Rocky Mountain PADD region meet the biorefinery location criteria (Parker et al., 2010) and that region is therefore excluded from this analysis. The weekly price data for gasoline and diesel fuel is used to calculate a regional transportation fuel price factor for each PADD region, with the weekly U.S. price serving as the baseline.

The EIA (EIA, 2011) also forecasts annual gasoline and diesel fuel prices through 2035. The 20-year average forecast post-tax prices for these are \$0.88/liter and \$0.91/liter, respectively. The regional transportation fuel factors (see

Table 3) are applied to these forecast prices to calculate the 20-year average forecast post-tax prices for gasoline and diesel fuel in each region. Finally, 20-year average forecast pre-tax prices for each PADD region are calculated for each transportation fuel by subtracting an amount equal to the sum of the federal excise fuel tax (\$0.05/liter for gasoline and \$0.06/liter for diesel fuel) and the average state excise fuel tax for the appropriate region from the post-tax price (see

Table 3) (API, 2012). The process model employed in this analysis assumes that the transportation fuels produced via fast pyrolysis and hydroprocessing are 50 wt% gasoline and 50 wt% diesel fuel (Wright et al., 2010a). Therefore the resulting gasoline and diesel fuel 20-year forecast pre-tax prices for each state according to their respective PADD regions are averaged to calculate the transportation fuel market price used in this analysis (see Table 1).

Table 3. EIA PADD regions and region fuel factors for states analyzed (EIA, 2012b)

EIA PADD Regions	**States analyzed**	**Region fuel factor**		**Region avg. fuel tax ($/liter) (API, 2012)[a]**	
		Gasoline	*Diesel*	*Gasoline*	*Diesel*
Central Atlantic	PA	1.02	1.05	0.13	0.15
Gulf Coast	AL, AR, LA, MS, TX	0.95	0.97	0.10	0.12
Lower Atlantic	FL, GA, NC, SC, VA, WV	0.97	0.98	0.12	0.14
Midwest	IA, IL, IN, KS, KY, MI, MN, MO, NE, OH, OK, SD, TN, WI	0.98	0.99	0.12	0.13
New England	ME	1.02	1.06	0.12	0.14
West Coast	CA, OR, WA	1.10	1.07	0.13	0.15

[a] Includes federal excise taxes of $0.05/liter for gasoline and $0.06/liter for diesel fuel.

Process model description

The fast pyrolysis and hydroprocessing biorefinery modeled here employs the following steps: feedstock pre-processing, fast pyrolysis, solids removal, bio-oil recovery, heat generation, hydrotreating, hydrocracking, and refining (see Figure 1) (Brown et al., 2013). Feedstock preprocessing consists of drying to 7 wt% moisture content or lower and chopping and grinding to 3mm dia. particles. Properties of the different feedstocks considered are presented

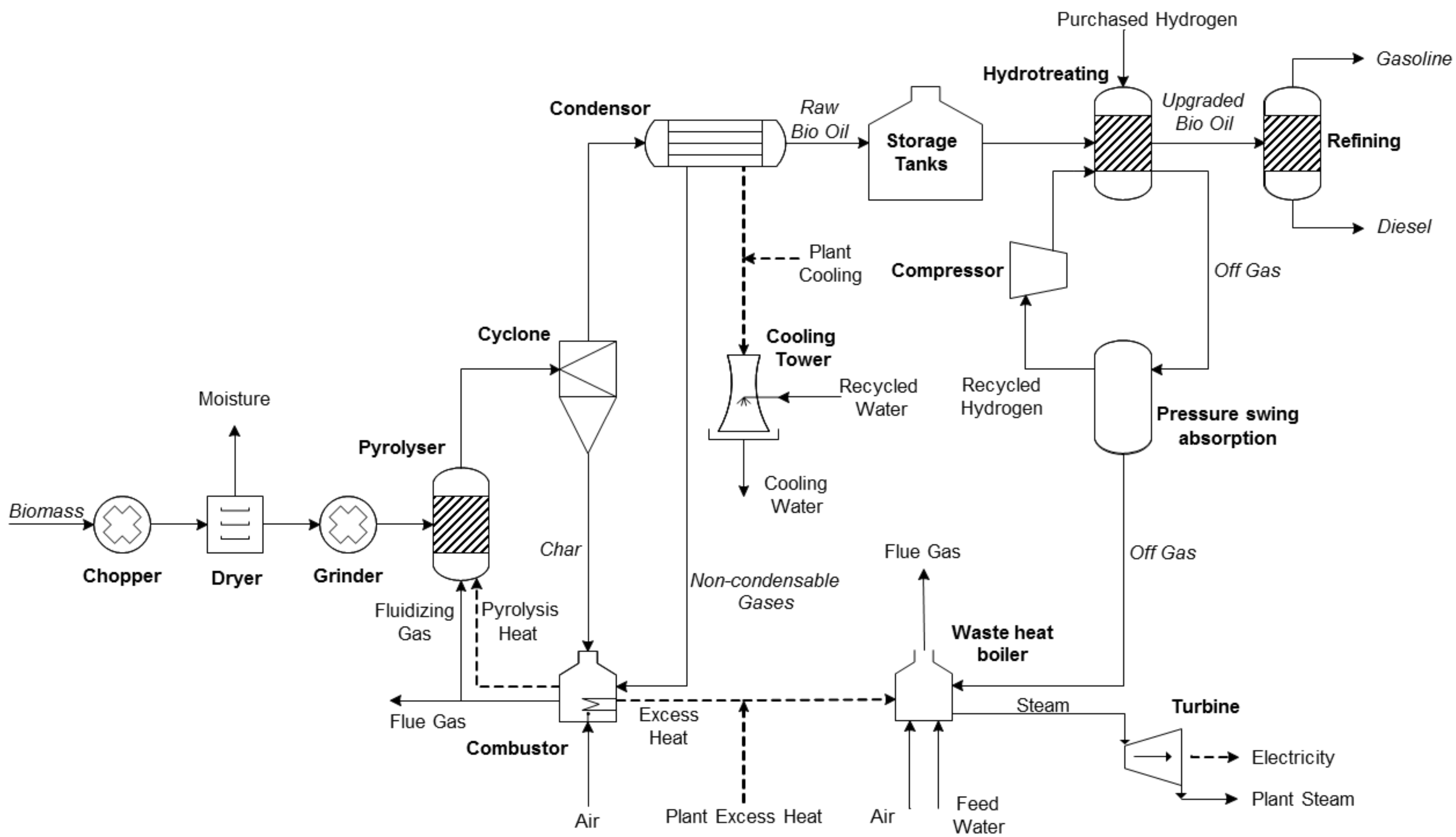

Figure 1. Schematic of fast pyrolysis and hydroprocessing system

Table 4. Pyrolysis consists of rapidly heating the feedstock in a fluidized bed reactor at 480°C to produce bio-oil, NCG, and char. Yields are dependent on feedstock (see

Table **2**). Cyclones operating at combined efficiency of 90% separate the char and ash from the pyrolysis vapors, which are then cooled, condensed, and delivered to an electrostatic precipitator where aerosols are separated from the NCG. The char and NCG are combusted to provide process heat and electricity; excess electricity is sold to the grid for $0.061/kWh, which is the 20-year projected industrial electricity price as calculated by the EIA (EIA, 2011).

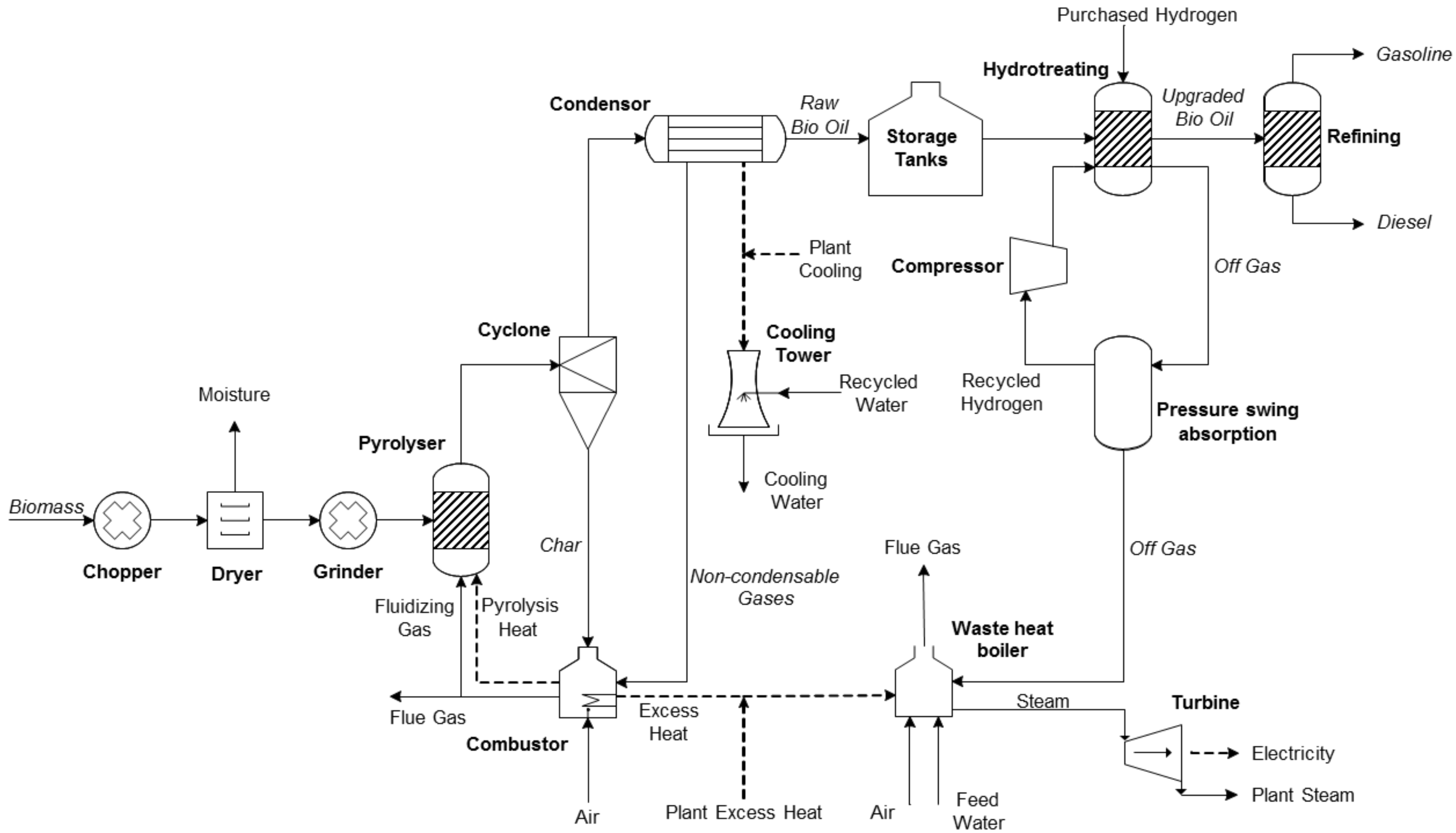

Figure 1. Schematic of fast pyrolysis and hydroprocessing system

Table 4. Properties of different feedstocks

Ultimate analysis (dry basis)	**Biomass value (wt%)**				
	Douglas fir (Parikh et al., 2007)	*Oak*[a]	*Pine (Oasmaa et al., 2010)*	*Stover (Wright et al., 2010a)*	*Switchgrass (Boateng et al., 2007)*
Ash	n/a	n/a	0.1	6.0	2.6
Carbon	56.2	48.7	50.5	47.3	47.5
Hydrogen	5.9	6.8	6.4	5.1	6.8
Nitrogen	0.0	0.1	<0.1	0.8	0.5
Sulfur	0.0	0.0	0.0	0.2	0.0
Oxygen	36.7	44.0	43.0	40.6	42.5
Proximate analysis (wet basis)	**Element value (wt%)**				
Moisture	n/a (dry basis)	3.9	9.5	25.0	2.7
Fixed carbon	25.8	12.6	13.9 (Cetin et al., 2005)	17.7	13.8
Volatile matter	73.0	81.9	84.0	52.8	81.2
Ash	1.2	1.7	0.1	4.5	2.5

[a]R.C. Brown, pers. comm., 2012.

Bio-oil upgrading is accomplished via 2-stage hydrotreating and hydrocracking. The effect of hydrotreating is to remove sulfur and nitrogen and deoxygenate the bio-oil. The first stage (hydrotreating) combines the bio-oil with 4 wt% hydrogen and reacts them in the presence of a cobalt-molybdenum catalyst at 2500 psig and 240°C to improve bio-oil stability. The second stage hydrotreatment fully deoxygenates the stabilized bio-oil to hydrocarbons at 2015 psig and 370°C. Unreacted hydrogen is recycled back to the hydrotreater via a hydrogen compressor and pressure swing adsorption unit. Merchant hydrogen is purchased for $1.50/kg (Wright et al., 2010b).

After separating gasoline and diesel fuel through a series of columns the high molecular residue is hydrocracked at 1280 psig and 427°C to yield additional gasoline and diesel fuel. A fuel yield of 41 wt% from the feedstock bio-oil is assumed (Elliott et al., 2009) evenly split between gasoline and diesel fuel (Holmgren et al., 2008).

Baseline total purchased equipment costs (TPEC) are estimated using Aspen Process Economic Analyzer™ software. Peters and Timmerhaus factors are employed to calculate baseline total project investment (TPI) (see Table 5) (Peters et al., 2002). Project capital is assumed to be equally derived from debt and equity with an interest rate of 7.5% on the debt, reflecting the additional risk of employing a new pathway (Anon, 2012d). Annual operating cost is the sum of variable operating costs and fixed operating cost. The variable operating cost is a function of fuel production capacity and in this analysis is the difference between the summed input costs (feedstock, hydrogen, catalyst, process water, and solids disposal) and the co-product credit for electricity. The fixed operating cost is the sum of labor, overhead, maintenance, and insurance and taxes (see

Table 6).

Table 5. Methodology for nth plant capital cost estimation (Peters et al., 2002)

Parameter	*Assumption*
Total purchase equipment cost (TPEC)	100%
Purchased equipment installation	39%
Instrumentation and controls	26%
Piping	10%
Electrical systems	31%
Buildings (including services)	29%
Yard improvements	12%
Service facilities	55%
Total installed cost (TIC)	TPEC * installation factor (3.02)
Indirect cost (IC)	0.89 * TPEC
Engineering	32%
Construction	34%
Legal and contractors fees	23%
Total direct and indirect costs (TDIC)	TIC + IC
Contingency	20% of TDIC
Fixed capital investment (FCI)	(TDIC + contingency) * LF[a]
Working capital (WC)	15% of FCI
Land use	6% of TPEC
Total project investment (TPI)	FCI + WC + Land

[a] Location factor.

Table 6. Methodology for nth plant fixed operating cost estimation (Wright et al., 2010b)

Parameter	*Assumption*
Labor	(Wright et al., 2010b)
Overhead	60% of labor and supervision
Maintenance	2% of TPI
Insurance and taxes (I&T)	1.5% of TPI
Total fixed operating costs	**Labor + Overhead + Maintenance + I&T**

A modified version of a discounted cash flow rate of return (DCFROR) spreadsheet developed by the National Renewable Energy Laboratory (NREL) (Wright et al., 2010b) is employed to calculate a 20-year IRR and a NPV with a 10% discount rate. Both IRR and NPV are measures of economic feasibility and are useful for scenarios in which both the input costs and the output market values are known. NPV is most appropriate for comparisons of mutually exclusive projects for which capital costs vary (Couper, 2003; Park, 2011). However, IRR is widely used in the literature for reporting the results of techno-economic analyses (Brown et al., 2012; Haro et al., 2013; Piccolo and Bezzo, 2009; Zhang et al., 2013), so it is also calculated here.

NPV is calculated as a function of the summed annual cash flows for the facility life and the discount rate. Annual cash flow is calculated as a function of project income and outlays via the following formula (Brown, 2003):

$$A_{CF} = A_R - (A_{OE} + A_{LP} + A_{IT}) \qquad (1)$$

where A_{CF} is annual cash flow, A_R is annual revenue, A_{OE} is annual operating expenses, A_{LP} is annual loan payment, and A_{IT} is annual income tax. The methodology for calculating each constituent part is presented in Figure 2.

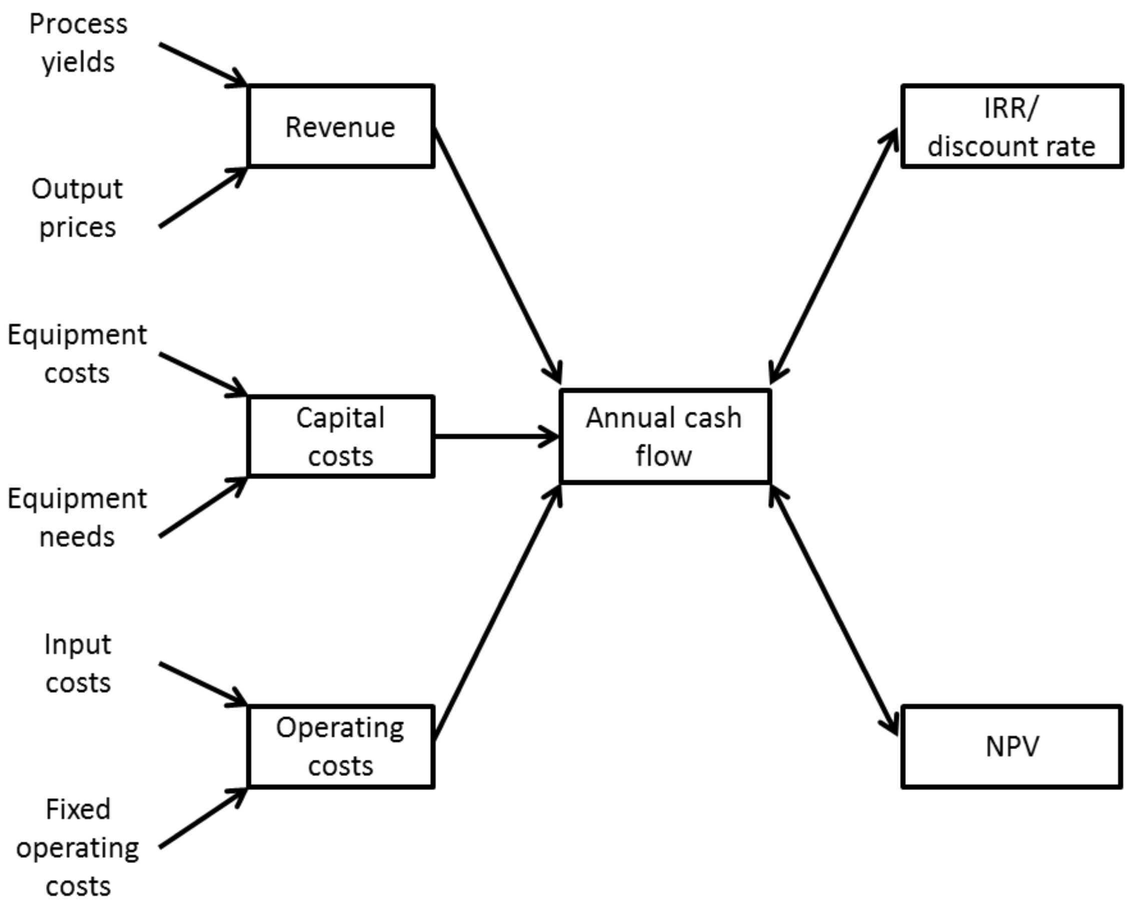

Figure 2. Flow diagram for calculating annual cash flow

NPV is calculated as a function of capital costs, operating costs, and discount rate (Brown, 2003):

$$NPV = \sum_{n=0}^{N} A_{CF}/(1+r)^n \qquad (2)$$

where *n* is the year, *N* is the total number of years, and *r* is the discount rate. A positive NPV represents an investment return that exceeds the discount rate, whereas a negative NPV represents a return below the discount rate.

IRR is calculated using the same formula as NPV. Rather than solve for NPV, however, the equation is used to calculate the discount rate that will produce a NPV of zero. This is a trial-and-error calculation requiring multiple iterations and this analysis employs Microsoft Excel to complete it. A positive IRR represents a positive return on investment.

Results

The process model simulates the production of gasoline, diesel fuel, and electricity via the fast pyrolysis and hydroprocessing of 2000 metric tons per day (MTPD) of feedstock. Total installed costs and total project investment for the baseline scenario are $234 million and $363 million, respectively (see Figure 3). Annual operating costs for the baseline scenario are $84 million; electricity is negative to represent its sale to the grid as a by-product (see Figure 4). Twenty year IRR and NPV for the baseline scenario are 12.1% and $55.9 million, respectively.

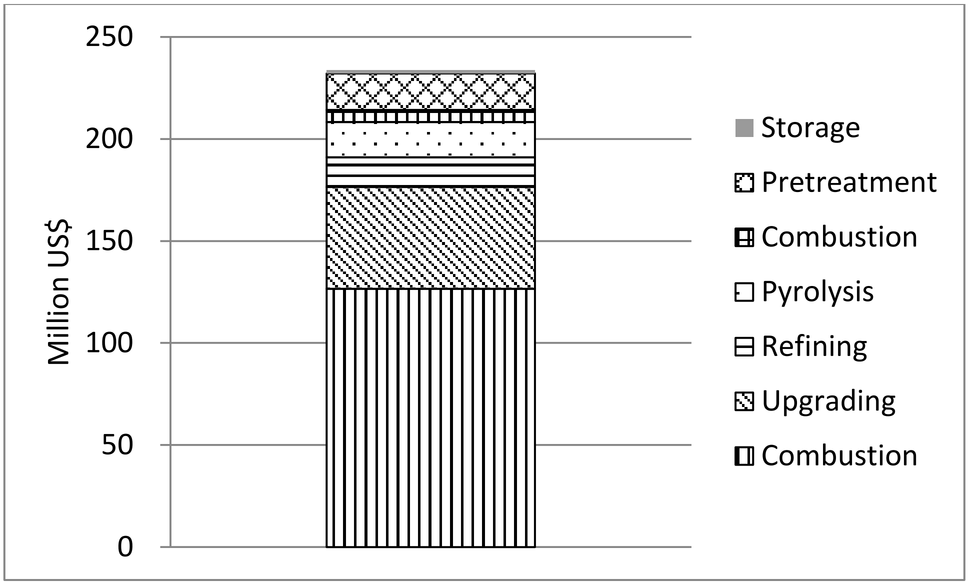

Figure 3. Installed equipment costs for baseline 2000 MTPD fast pyrolysis and hydroprocessing biorefinery

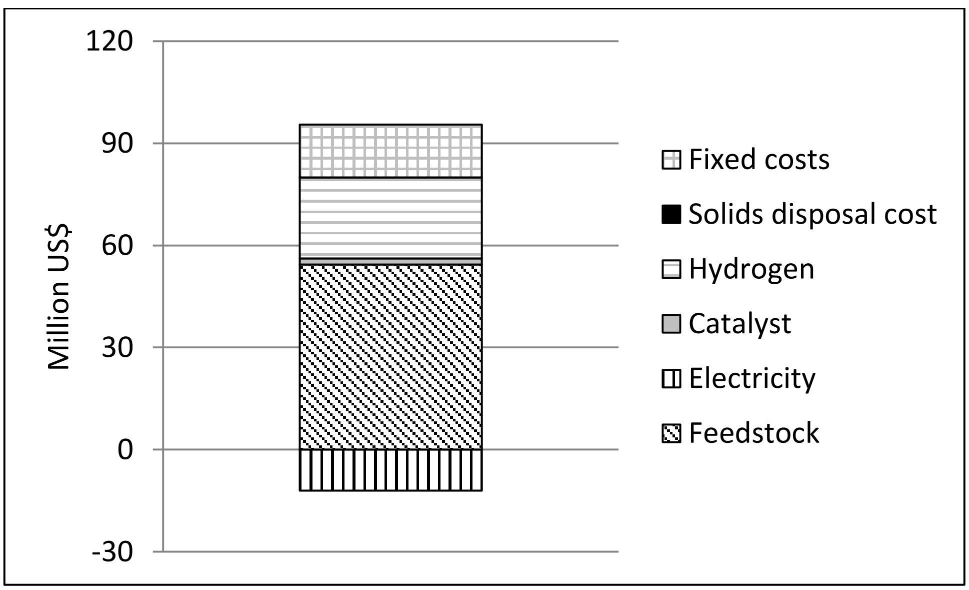

Figure 4. Annual operating costs for baseline 2000 MTPD fast pyrolysis and hydroprocessing biorefinery (excludes capital depreciation and income tax)

Twenty year IRR and NPV vary significantly for the different state scenarios (see Figure **5** and Figure 6). The Illinois scenario has the lowest IRR and NPV at 7.4% and -$79.5 million, respectively, and Georgia has the highest IRR and NPV at 17.2% and $165.5 million. The mean and median IRRs and NPVs for all state scenarios are 11.5% and $36.8 million and 10.9% and $24.1 million, respectively, with a standard deviation of 2.8% and $68.9 million.

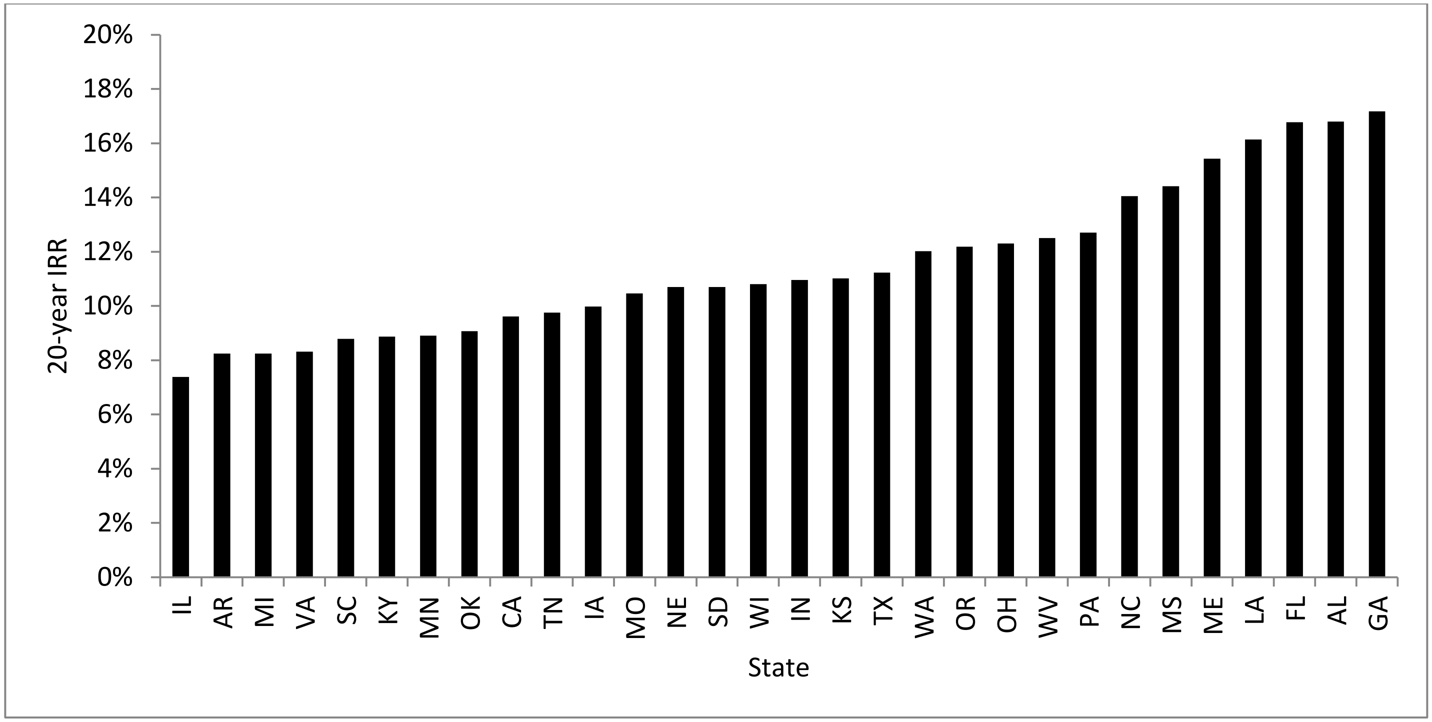

Figure 5. 20-year IRR for each state scenario

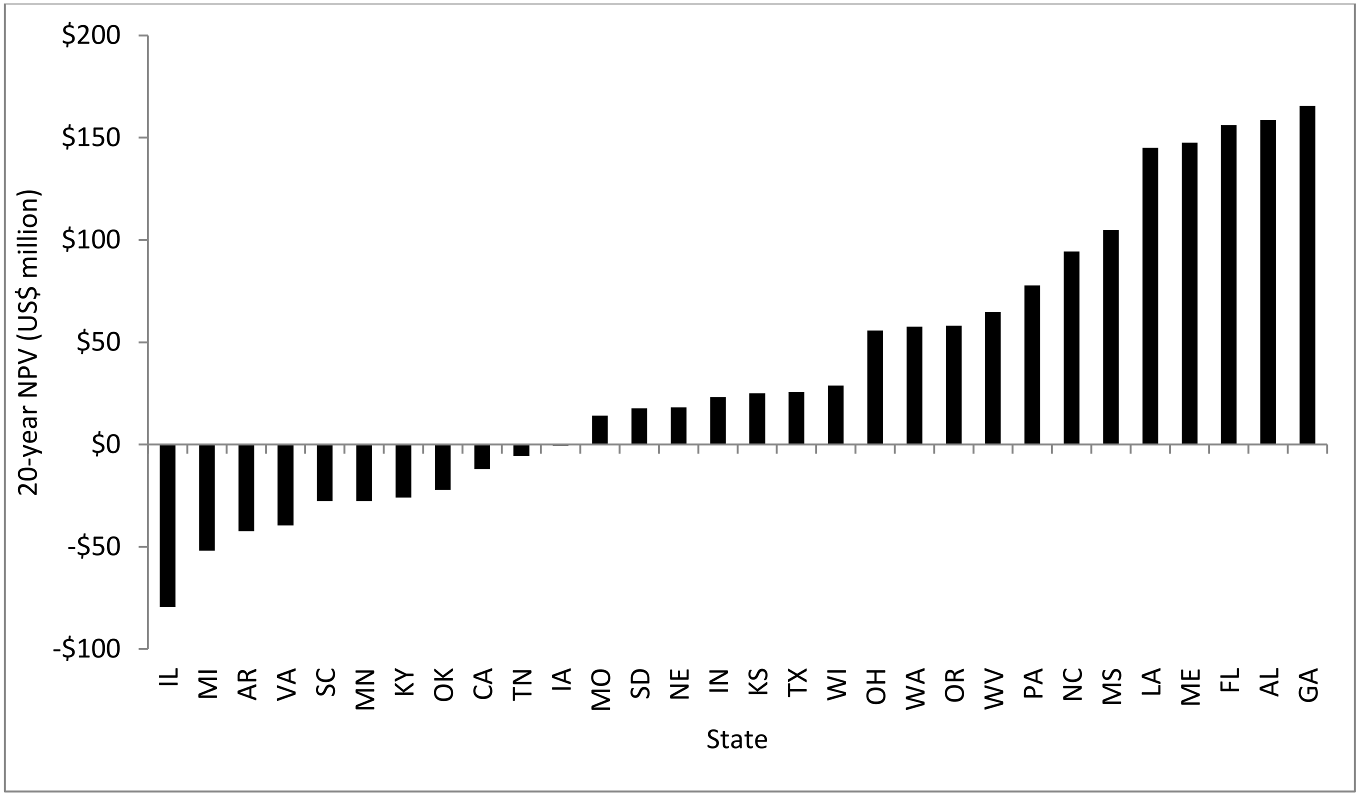

Figure 6. 20-year NPV for each state scenario

A sensitivity analysis is employed using pessimistic, base case, and optimistic scenarios using the parameter ranges from Table 1 to determine which of the factors considered have the greatest impact on 20-year NPV (see Figure 7). NPV is very sensitive to location capital cost factor, bio-oil yield, feedstock cost, and fuel market value. The base case NPV is $55.9 million. Location factor has the greatest impact on NPV, with factors of 1.36 and 0.89 generating NPVs of -$47.2 million and $111.4 million, respectively. Bio-oil yield also has a major impact on NPV, with yields of 58 wt% and 70 wt% resulting in NPVs of $-32.4 million and $140.3 million, respectively. Feedstock cost, fuel market value, and state corporate income tax rate do not have as much of an impact and while the pessimistic scenarios for each reduce NPV, none of the three yield a negative NPV. The optimistic scenario for fuel market value is influential, however, with an increase of $0.06/liter resulting in an increase to NPV of $68.1 million.

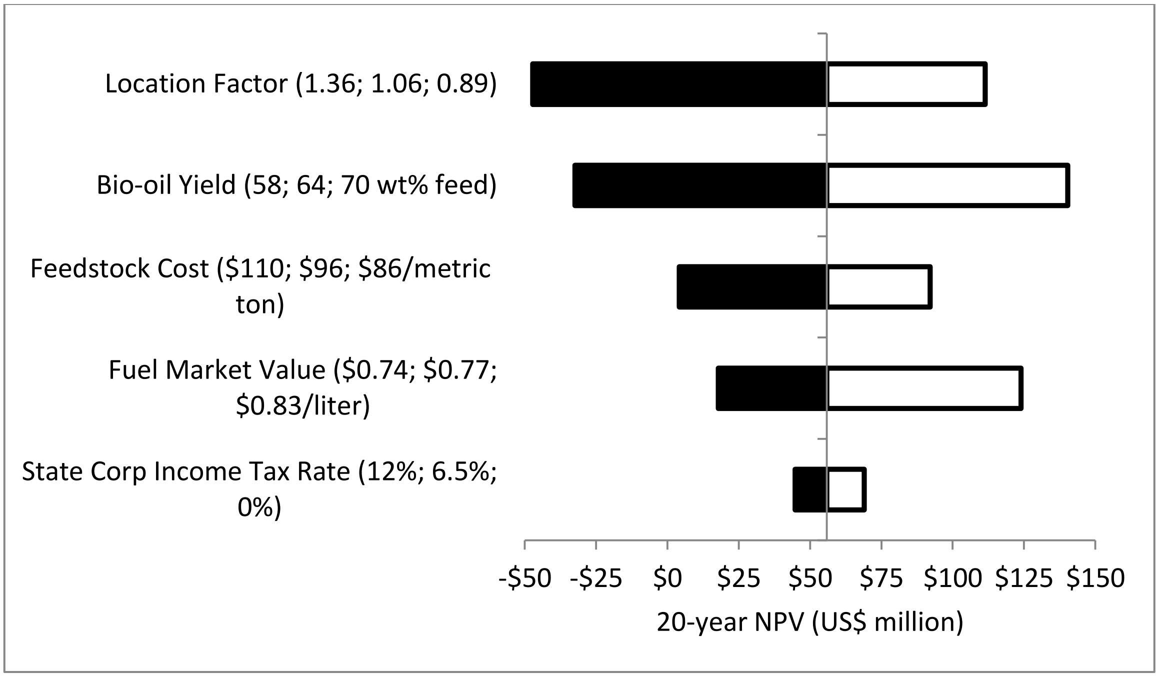

Figure 7. Sensitivity analysis for 2000 MTPD fast pyrolysis and hydroprocessing biorefinery

While previous analyses have produced similar conclusions regarding sensitivity to feedstock cost, bio-oil yield, and fuel market value (Brown et al., 2012; Wright et al., 2010a), this is the first analysis to determine that the economic feasibility of a fast pyrolysis and hydroprocessing biorefinery is also sensitive to biorefinery location. A state such as Georgia with low capital costs and close proximity to a feedstock characterized by a high bio-oil yield has a significant advantage over a state such as Illinois, which is burdened by both high capital costs and a lower-yielding bio-oil feedstock. The relatively low sensitivity of biorefinery NPV to state income tax rate suggests that the commonly-used tool of tax policy can do relatively little to overcome a state's inherent advantages or disadvantages.

These results also suggest that future TEAs of biorenewable pathways should consider location as a factor, particularly when a specific feedstock is being analyzed. Quantifying the economic feasibility of a stover fast pyrolysis biorefinery on a U.S. Gulf Coast capital cost basis will generate a result that either underestimates the biorefinery capital costs or underestimates the feedstock bio-oil yield, due to the fact that both are greater in the Gulf Coast region (see Table 1).

A review of the current state of commercialization in the U.S. shows a correlation between the locations of commercial-scale cellulosic biorefineries employing thermochemical pathways (both constructed and under construction) and the state rankings in this analysis. The gasification company Lanzatech is retrofitting a biorefinery purchased from failed biofuel producer Range Fuels in Georgia (#1 in this analysis). Initial capacity will be 15 MLY and final expected capacity is 379 MLY (Garthwaite, 2012). Coskata, another gasification company, is building a biorefinery in Alabama (#2 in this analysis) with an initial capacity of 61 MLY and final expected capacity of 208 MLY (Glick, 2011). Gasification-based Sundrop Fuels is building a 189 MLY biorefinery in Louisiana (#4 in this analysis) (Anon, 2012c). In Mississippi (#6 in this analysis), two companies are building commercial-scale thermochemical biorefineries: catalytic pyrolysis company KiOR is constructing biorefineries with a total capacity of 167 MLY (Goossens, 2011) and gasification company Rentech is constructing a 946 MLY biorefinery .

The present analysis is limited to fast pyrolysis and hydroprocessing biorefineries that employ cellulosic feedstocks. Further study is required to analyze biochemical, hybrid, and other kinds of thermochemical pathways using a similar analytical framework. Pathways producing advanced biofuels from lipid feedstocks should also be considered, as these represent a major source of existing advanced biofuels capacity both in the U.S. and globally (Lane, 2010). Additionally, further analysis is needed to determine if the economic feasibility of biorefineries is similarly sensitive to county-level and specialized state-level factors, such as the interest-free $75 million loan awarded to KiOR by the state of Mississippi for the construction of a biorefinery there (Dolan, 2011).

Policy implications

The sensitivity of the fast pyrolysis and hydroprocessing pathway to state- and region-specific factors indicates that the RFS2 promotes the production of cellulosic biofuel via the pathway in the states in which production costs are lowest. Consequently, future cellulosic biofuel RIN core values, which operate as a function of production costs, could be very sensitive to the location of cellulosic biofuel facility construction. The results of this analysis illustrate the importance of considering location sensitivity for other cellulosic biofuels pathways under both the biochemical and thermochemical platforms, as location-specific factors can be expected to influence cellulosic biofuel RIN values. The current trend in techno-economic analyses is to focus on facilities located within a specific region, with the U.S. Gulf Coast frequently analyzed by default. While important for serving as a starting point in the quantification of the technical and economic feasibility of novel biofuel pathways, these analyses necessarily ignore location-specific factors that can have a significant impact on the economic feasibility of the pathway facility being considered.

Further research is needed to determine (1) whether other cellulosic biofuel pathways exhibit a similar sensitivity to facility location; (2) if all cellulosic biofuel pathways are uniformly sensitive to locations, or if pathway sensitivity instead varies according to different combinations of pathways and locations combinations; (3) whether any difference in sensitivity to facility location correlates to the biochemical and thermochemical platforms; and (4) the effect of feedstock seasonality on pathway economic feasibility as a location-specific factor.

Conclusion

This paper calculates the 20-year IRR and NPV for a 2000 MTPD fast pyrolysis and hydroprocessing biorefinery under 30 different state scenarios. Each scenario accounts for the following state-specific factors: feedstock type, feedstock cost, bio-oil yield, location capital cost factor, state corporate income tax rate, and transportation fuel price. Feedstock cost ranges from \$86-\$110/MT; bio-oil yield from 57.8 wt% to 70.1 wt%; location capital cost factor from 0.89 to 1.36; state corporate income tax rate from zero to 12%; and transportation fuel price from \$0.74-\$0.83/liter.

Feedstock cost, bio-oil yield, location capital cost factor, and transportation fuel price are all found to have a significant impact on biorefinery IRR and NPV. This results in a wide range of IRRs and NPVs for different state scenarios, from 7.4% and -$79.5 million in Illinois to 17.2% and $165.5 million in Georgia, respectively. This analysis demonstrates that the economic feasibility of a fast pyrolysis and hydroprocessing biorefinery is very sensitive to location on a state basis within the U.S. Techno-economic analyses can achieve greater accuracy by accounting for regional differences, especially when a specific feedstock type is assumed to be employed for a biorefinery. Finally, the results of this analysis correlate with the locations of cellulosic thermochemical biorefineries in the U.S. (both those that have been constructed and are under construction), where capacity is primarily found in the states of Alabama, Georgia, Louisiana, and Mississippi.

The finding that the economic feasibility of fast pyrolysis and hydroprocessing facilities is strongly sensitive to facility location suggests that specific states and regions will be the focus of pathway commercialization efforts. Should other cellulosic biofuel pathways to also exhibit a similar sensitivity to location, then it is possible that cellulosic biofuel commercialization will be focused on a comparatively small section of the U.S. Further research is needed to identify whether other cellulosic biofuel pathways exhibit a similar sensitivity to facility location and, if so, whether there is a correlation between pathway type and location.

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